# Project Closeout Report

# BLIP Raster System AIP

**at the**
**Collider-Accelerator Department**
**at**
**Brookhaven National Laboratory**
**Upton, NY**

**for the**
**U.S. Department of Energy**
**Office of Science**
**Office of Nuclear Physics (SC – 26)**

**Date**
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**Project Closeout Report for BLIP Raster System AIP**
**at the**
**Collider-Accelerator Department**
**at**
**Brookhaven National Laboratory**

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# 1. Introduction

Demand for two important isotopes produced at the Brookhaven Linac Isotope Producer (BLIP), Sr-82 and Ge-68, has historically exceeded capacity. The BLIP Raster Project has provided the capability to more evenly distribute the beam on target, which results in decreased total power density. This allows the average beam current on target to be increased, which directly results in increased product.

The goal of the project was to design and install a beam raster system in BLIP with a rapid (5 kHz) scan frequency. The original anticipated raster pattern was: three consecutive beam pulses rotated in a circle of diameter 19.5mm radius, then one beam pulse rotated in a circle of diameter 6.5mm radius. After further analysis and commissioning with beam, the optimum raster pattern for Sr-82 production has been determined to be: four consecutive beam pulses rotated in a circle of diameter 11.5mm radius, then one beam pulse rotated in a circle of diameter 4.5mm radius. This pattern is repeated so that a nearly uniform beam intensity profile is achieved. In this manner the beam completes 2.25 rotations per beam pulse of 450 µs length and the power density is reduced by at least a factor of four. This is intended to increase isotope yield and sharply reduce target fatigue. The project initiated in 1QFY14 and was scheduled to be completed 1QFY17. All Key Performance Parameters (KPPs) were achieved by the end of 1QFY16.

Previous efforts to improve supply with increased current were difficult. The Linac succeeded in increasing the maximum beam current to BLIP to 125 µA and achieving an average beam current of 110 µA. The beam was pulsed and the pulse-averaged beam current potential was as high as 43 mA. Combined with a sharply peaked Gaussian-shaped beam intensity profile this created very high power density at the beam spot center (>4 $kW/cm^2$) and caused target lifetime and reliability issues due to overheating, as well as somewhat erratic isotope yields. A short term solution was to limit Linac average current to no more than 115 µA. The implementation of the BLIP Raster System AIP has provided the ability to increase the Linac average current on target to over 160 µA.

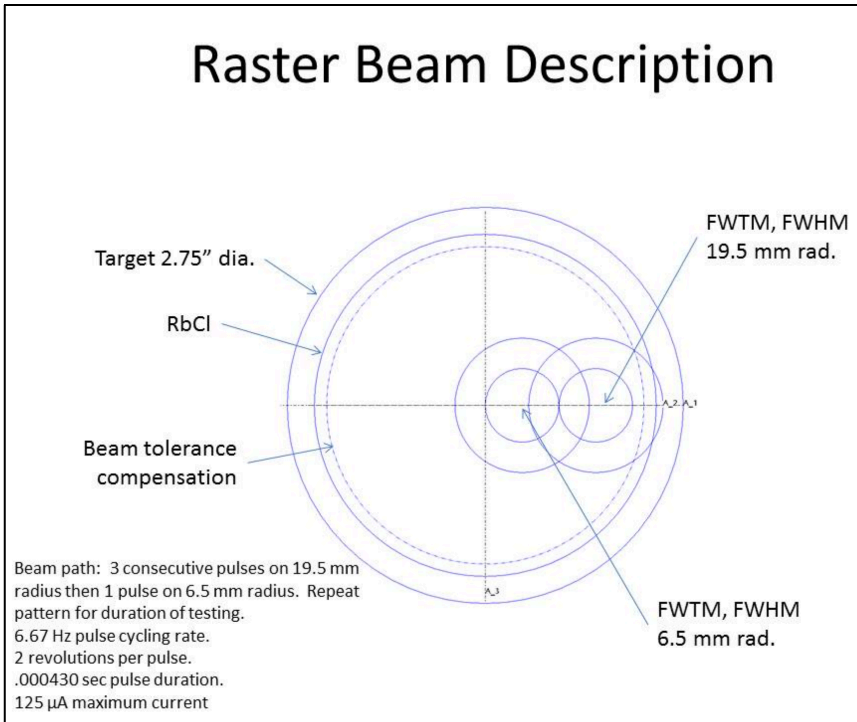
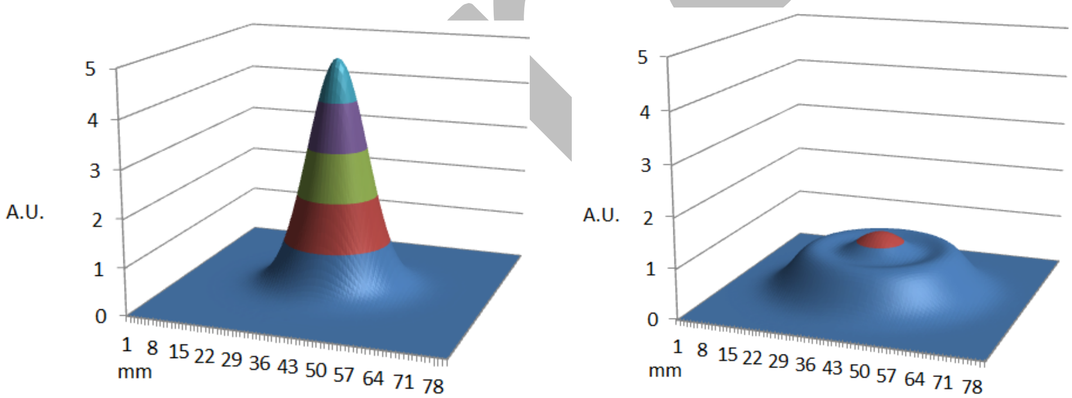



Figure 1: Raster Beam Description (original proposal)






<u>Beam distribution without raster</u>
FWHM: 6.5 mm
FWTM: 11.85 mm

<u>Beam distribution with raster</u>
Repeating raster pattern:
- 3 linac beam pulses at 19.5 mm
- 1 linac beam pulse at 6.5 mm

Figure 2: Simulated beam distribution on target (original proposal)

Sr-82 is created by irradiating RbCl pressed pellet targets. RbCl has poor thermal conductivity, and with a fixed Gaussian beam spot the salt melts only in the beam strike area. Upon melting the RbCl expands 21% and moves outward, refreezing into void space on the target's periphery, and reducing the amount of RbCl remaining in the irradiation zone by an estimated 10%. This effect also shifts the proton energy on downstream targets higher than optimum leading to reduced and variable Sr-82 yield. The net impact on yield is as much as 20%. The raster parameters, 5 kHz sweep with dual radius, are driven by the thermal properties of RbCl. In addition the raster minimizes material creep as most of the target is consistently molten, but with lower overall temperatures than previously achieved. The lower average salt temperatures can, in principle, allow safe increases in beam current up to 240 µA, enabling target survival if a future project to double the average Linac beam current is approved and implemented. This compares favorably to the present maximum average beam current of 230 µA at the Isotope Production Facility at LANL where a single radius raster system has already been implemented.

By spreading out the power density, the raster system is beneficial for all targets as it improves reliability. In 2011 and 2012 the Ge-68 target failure rate due to target leaks at high temperature was 50%, which was unacceptable. To assure better target survivability, in 2013 the beam current incident on this Ga metal target was limited to only 75 µA, thus reducing yield by 30%. By decreasing peak temperature by an estimated 200$^{o}$C with the raster, it was hoped that these targets would survive at higher beam current. A Ga metal target was irradiated at 150 µA with rastered beam in January 2016 but failed after 2.8 days. Therefore, peak power density is not likely the cause of the Ga target failure, but further investigation is required. A plan for analysis of the Ga target failure is presented in Attachment A of this report.

The BLIP raster system project scope included the development and installation of rapid cycling magnets and associated power supplies and controls to continuously scan the beam in a circular fashion on the target. New diagnostic devices in the BLIP beam line were also developed and installed to enable measurement of the beam parameters, including a laser profile monitor, beam position monitor and two plunging multiwire profile monitors. In addition, two new beam current monitors were installed to replacethe 40+ year old, radiation damaged units. Beam intensity on target is critical information for the production program in order to predict radioisotope quantity, and for research projects to measure nuclear reaction cross sections of desired radioisotopes. An interlock system to inhibit beam if not rastering as expected was also developed and installed to prevent target damage due to the smaller beam profile and higher beam currents used with the new raster system.

## 2. Management

The Federal Program Manager for the BLIP Raster System AIP project was Marc Garland and the Contractor Project Manager at BNL was Robert Michnoff.

# 3. Project Baseline

## 3.1. Technical Scope and Deliverables Baseline

The project scope consisted of the design, fabrication, installation, and commissioning of the BLIP Raster system with the components listed below and shown in figure 3 below.

**Raster System components**:

- 1 raster magnet
- 2 raster magnet power supplies (X and Y) and associated electronics
- 2 plunging harps (multi-wire) and associated electronics
- 1 laser profile monitor and associated electronics
- 1 dual plane beam position monitor and associated electronics
- 2 beam current transformers and associated electronics
- 2 fixed collimators (6.5”, 4.5”)
- 3 aluminum bellows
- 1 viewport and electron suppressor
- controls equipment
- beam interlock system

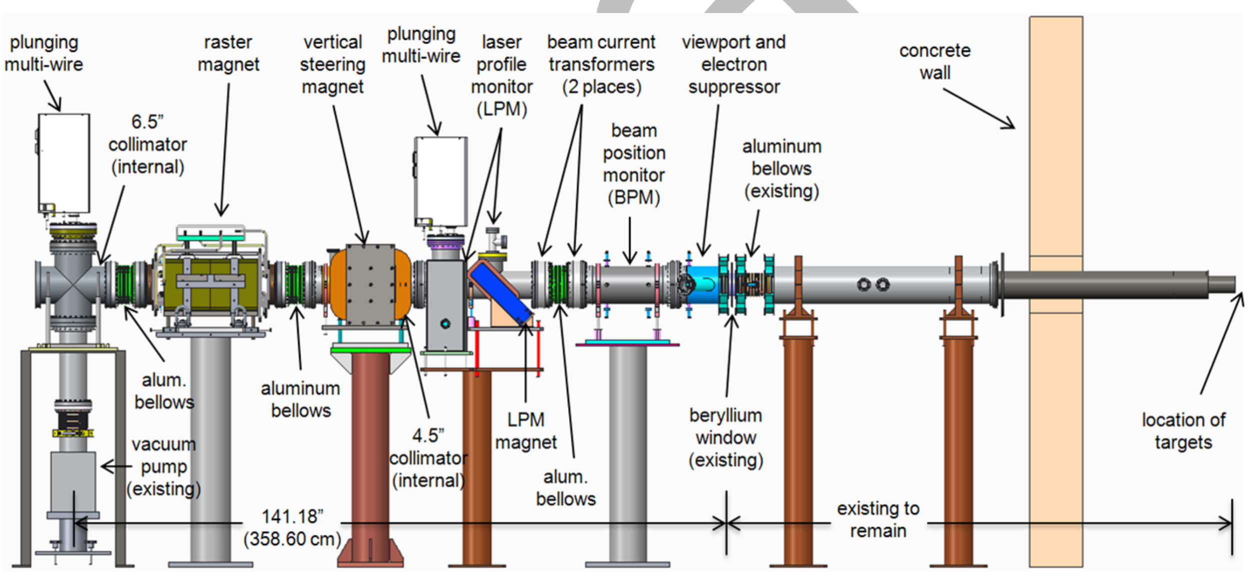



Figure 3: New BLIP beamline layout

3.2. Key Performance Parameters (KPPs)

In December 2015 the following key performance parameters (KPPs) that define successful completion of the project were satisfied:

- The raster magnets, power supply and associated beamline vacuum components and electronic equipment are installed. This includes components in the tunnel as well as in the BLIP control room.
- The beam is modulated horizontally and vertically to produce 5 kHz circular rastering of the beam with a fixed radius on the BLIP target.
- The average beam current is limited to 125 μA, the current that is currently used for non-rastered operation in order to provide additional safety against target damage.

3.3. Ultimate Performance Parameters (UPPs)

The Ultimate Performance Parameters (UPPs) for the BLIP Raster System consist of:

(1) The circular rastering of the beam will be configurable to occur at 2 different radii. The anticipated operation is to raster the beam at a radius of 19.5 mm for 3 consecutive 450 μs long pulses (2.25 rotations per pulse), then raster the beam at a radius of 6.5 mm for one pulse, and repeat the pattern. The system is presently operating at 2 different radii with the following repeating pattern: four consecutive 450 μs long pulses at a radius of 11.5 mm, then one pulse at a radius of 4.5 mm.

(2) A beam interlock system that allows for an average beam current of 140 μA.

UPP number (2) has been satisfied and typical average beam current is over 150 μA with up to 160 μA achieved. The beam interlock system is operating as expected and is providing target protection as designed.

Regarding UPP number (1), we are presently operating at 2 different radii, so that portion of the UPP has been satisfied. The typical repeating raster pattern beginning Tuesday March 22, 2016 for Sr-82 production (117 MeV beam energy) is 4 linac cycles at 12.5 mm (155 amps peak magnet current, at 5 kHz) and 1 linac cycle at 5.5 mm (71 amps peak magnet current, at 5 kHz). Prior to March 22, the repeating raster pattern was 4 linac cycles at 11.5 mm and 1 linac cycle at 4.5 mm.

Under the present and foreseeable future beam operating conditions, a radius as high as the 19.5 mm stated in UPP number (1) is not expected to be required. This is mainly because the actual transverse beam width is significantly larger than the beam width used for the raster simulation in figure 1 above. In fact, while operating at 200 MeV and an outside radius of 13.5 mm (225 A peak magnet current at 5 kHz), the collimator temperatures were heating excessively indicating that significant beam was falling outside the 4” collimator inside diameter. The large radius was subsequently decreased to 11.5 mm (191 A peak magnet current at 5 kHz).

In addition, since we do not fully understand the cause of the vacuum failure of the beam tube for the originally assembled magnet, we prefer to be conservative in the operating current of the raster magnet. This will help keep vibrations and temperature increases due to eddy currents at lower levels, thus limiting the chance of failure.

Although the power supply system is capable of operating at the original 318 amps peak magnet current at 5 kHz (to produce 19.5 mm radius at 200 MeV), we propose limiting the peak operating current to 260 A (15 mm radius at 200 MeV). This 15 mm maximum raster radius is not expected to be viable with present beam conditions (for the reasons explained above), and therefore will not limit isotope research and production performance parameters in any way. At this point in time, we do not expect to require a radius larger than 13.5 mm at 200 MeV, which is even below the 15 mm proposed maximum.

Operation with the present magnet has successfully been demonstrated at 260 A peak, 5 kHz without beam for several hours.

We therefore recommend that the UPPs be closed with the understanding that the raster radius will be limited to 15 mm maximum at 200 MeV with no sacrifices to the isotope research and production program based on the present and foreseeable future beam operating conditions.

### 3.4. Cost Baseline

The Total Project Cost was $4.5M dollars inclusive of $753k of contingency, funded by AIP funds.

Through June 2016, the project has accrued $3.95M of costs and $321k of contingency has been approved for project use plus an additional $349k has been approved for post-commissioning additional scope (BM1 magnet power supply replacement and Gallium target failure analysis). A proposal to use the remaining funding including contingency is provided in section 6 in this report.

### 3.5. Milestone Performance

The chart below shows the project milestones.

| BLIP Raster System - Milestones | Planned Q/FY | Actual/Forecast Q/FY |
|---|---|---|
| Project Start | 1QFY14 | 1QFY14 (A) |
| Designers assigned to project | 1QFY14 | 1QFY14 (A) |
| Access BLIP Spur | 1QFY14 | 1QFY14 (A) |
| PM trip to LANL | 2QFY14 | OBE |
| Current Transformers ordered | 2QFY14 | 2QFY14 (A) |
| Material ordered for Plunging Multiwire Profile monitor | 2QFY14 | 2QFY14 (A) |
| Decision on Rad Hard vs. periodic replacement | 3QFY14 | 3QFY14 (A) |
| Design Review & Accelerator Systems Safety Review | 4QFY14 | 3QFY14 (A) / 1QFY15(A) |
| Summer/Fall 2014 access to BLIP Tunnel | 1QFY15 | 1QFY15 (A) |
| All power supply purchases received | 2QFY15 | 2QFY15 (A) |
| Vacuum fabrication begins | 3QFY15 | 4QFY14 (A) |
| Magnet stand fabrication begins | 3QFY15 | 1QFY15 (A) |
| Vacuum Chamber pumpdown | 4QFY15 | 1QFY16 (A) |
| Summer/Fall 2015 access for BLIP Tunnel Installation | 4QFY15 | 4QFY15 (A) |
| Raster magnet available for installation | 1QFY16 | 1QFY16 (A) |
| Plunging Multiwire Profile Monitor available for installation | 1QFY16 | 1QFY15 (A) |
| Accelerator Systems Safety Review-installed | 1QFY16 | 1QFY16 (A) |
| Power supply installation | 2QFY16 | 1QFY16 (A) |
| DOE approval to operate | 2QFY16 | 1QFY16 (A) (Internal Approval) |
| Begin Raster System test without beam | 3QFY16 | 1QFY16 (A) |
| Confirmation of Rastering | 4QFY16 | 1QFY16 (A) |
| Project complete | 1QFY17 | 2QFY16 (A) |

## 3.6. Funding

Project funding received to date is \$4.47M. \$3.7M was received in FY 2014, \$613k was received in FY 2015, and \$152k has been received in FY 2016.

A summary of expenditures as of June 2016 is shown below.

| Raster AIP | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WBS | Account # | Title | FY14 Actuals | FY15 Actuals | FY16 Actuals | Project to date (PTD) costs* | Burdened Commit-ments | Cost & commit-ments | Original Budget at Comple-tion | Budget Changes | Current Budget at Comple-tion | Current Budget less actuals / commts |
| 1.1 | 70047 | Management | 56.2 | 160.2 | 44.8 | 261.3 | - | 261.3 | 266.4 | 0.0 | 266.4 | 5.1 |
| 1.2 | | Construction | 1,490.6 | 1,466.2 | 353.0 | 3,309.8 | - | 3,309.8 | 2,888.0 | 316.0 | 3,204.0 | (105.8) |
| *1.2.1* | *70048* | *Instrumentation* | *825.5* | *664.4* | *37.9* | *1,527.8* | - | *1,527.8* | *1,931.6* | *32.0* | *1,963.6* | *435.8* |
| *1.2.2* | *70049* | *Magnet and Vacuum* | *458.8* | *416.3* | *87.4* | *962.5* | - | *962.5* | *645.6* | *130.0* | *775.6* | *(186.9)* |
| *1.2.3* | *70050* | *Power Supplies* | *206.3* | *385.5* | *227.7* | *819.5* | - | *819.5* | *310.9* | *154.0* | *464.9* | *(354.6)* |
| 1.3 | 70051 | Installation | 99.1 | 149.1 | 30.9 | 279.1 | - | 279.1 | 510.9 | 5.0 | 515.9 | 236.7 |
| 1.4 | 70052 | Commissioning | - | - | - | - | - | - | 81.6 | 0.0 | 81.6 | 81.6 |
| 1.x | | Post-Commissioning | - | - | - | - | 101.5 | 101.5 | | 349.0 | 349.0 | 247.5 |
| *1.x.x* | *70054* | *BM1 Power Supply* | - | - | - | - | *101.5* | *101.5* | - | *249.0* | *249.0* | *147.5* |
| *1.x.x* | *70076* | *Misc. Spare Equipment* | - | - | - | - | - | - | - | *0.0* | - | - |
| *1.x.x* | *70077* | *Spare Raster Magnet* | - | - | - | - | - | - | - | *0.0* | - | - |
| *1.x.x* | *70078* | *Ga Target Failure Analysis* | - | - | - | - | - | - | - | *100.0* | *100.0* | *100.0* |
| | 70053 | Contingency | - | - | - | - | - | - | 753.0 | (670.0) | 83.0 | 83.0 |
| | | Total (Actual Cost of Work Performed) | 1,645.9 | 1,775.6 | 428.7 | 3,850.2 | 101.5 | 3,951.7 | 4,499.9 | 0.0 | 4,499.9 | 548.2 |

Note: Commissioning work was not charged to account 70052 but was instead charged to the respective system WBS account.

The original estimated cost to complete the project excluding contingency was \$3746.9k. The actual cost to complete the project KPPs and UPPs was \$3850.2k, which is 86% of the total original baseline budget of \$4499.9k including contingency. The remaining funding after completing the project was \$649.7k.

Therefore, the actual contingency used was \$103.3k of the original \$753k contingency, which is 14% of the original contingency amount, or 2.8% of the original estimated cost (excluding contingency) of \$3746.9k.

Of the remaining project funding of \$649.7k, \$349k has already been approved for additional scope (BM1 bending magnet power supply replacement and Gallium target failure analysis), and we propose to use the remaining \$300.7k to purchase high priority spare equipment.

## 3.7. Schedule

During the BLIP Raster AIP Technical, Cost, Schedule and Management Review in September 2013, a request was made to complete the project on a shortened time schedule, and complete the installation over two summer shutdown periods instead of the originally proposed three shutdown periods.

The project was completed on schedule in accordance with the aggressive shortened time scale.

## 4. Closeout Status

As of January 2016 all KPPs have been satisfied, and closeout of the UPPs is requested based on the explanation provided in section 3.3 of this report.

## 5. Beam Data

Figure 4 below shows one of the typical raster patterns used with beam for Sr-82 production. Following this figure are several beam phosphor images taken with various conditions, including raster on/raster off, 117 MeV, 200 MeV, and different raster patterns.

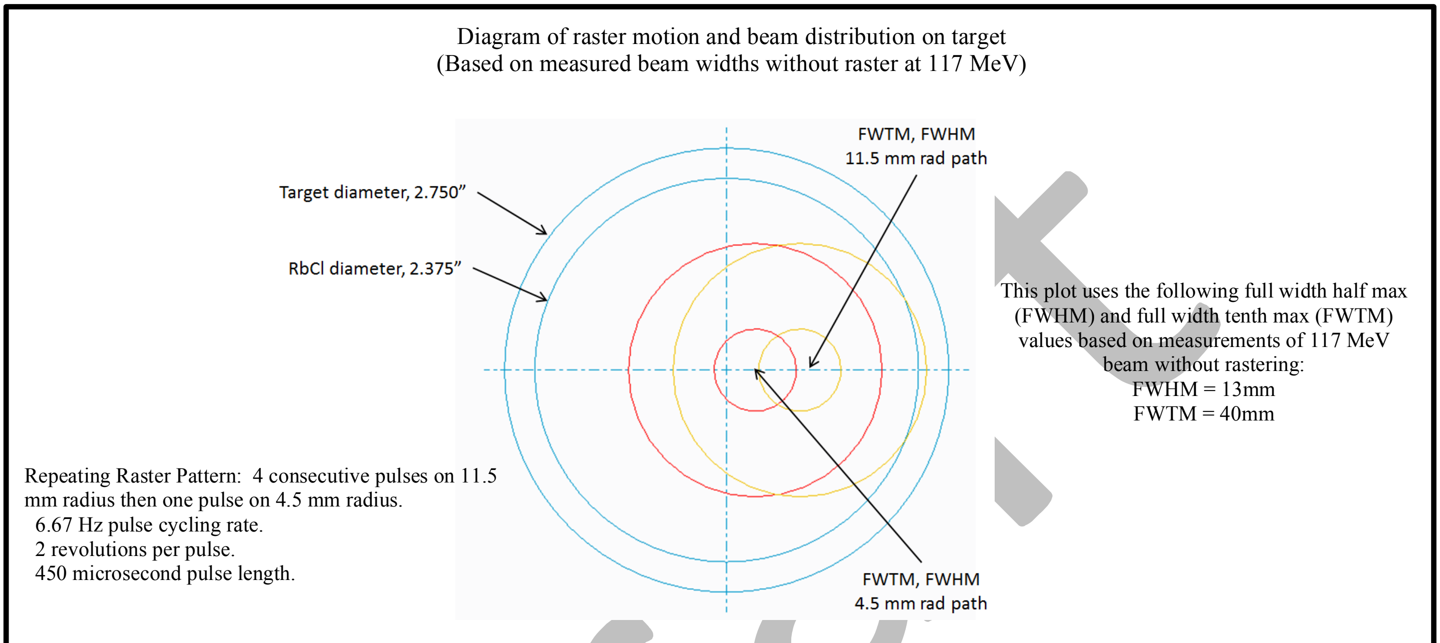



Figure 4: Raster beam diagram (used for operations from January 2016 to March 22, 2016). On March 22, 2016 the beam size was reduced to 10 mm FWHM and 23 mm FWTM, and the raster pattern was changed to the repeating pattern of 4 beam pulses at 12.5 mm radius and 1 beam pulse at 5.5 mm radius.

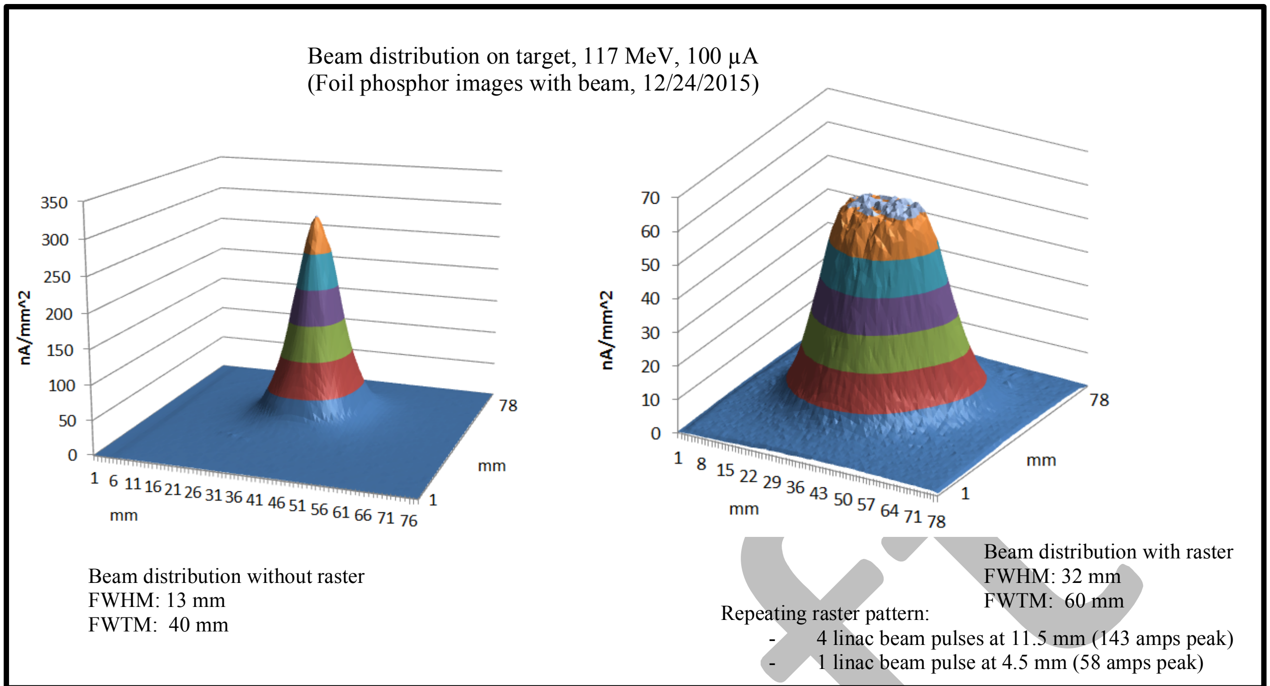



Figure 5a: Measured beam distribution on target with and without rastering, 117 MeV (Foil phosphor images with beam, 12/24/2015). Note different y-scales. Peak of non-rastered profile is about 5 times higher than the rastered beam profile.

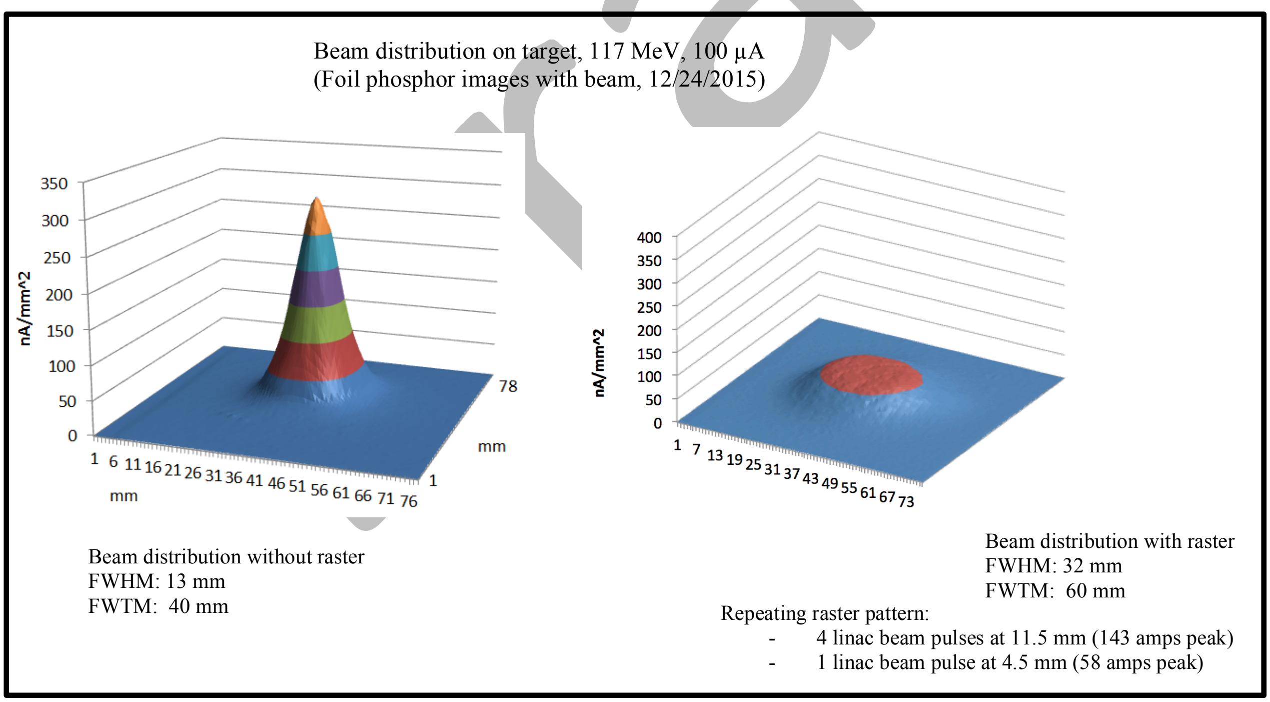
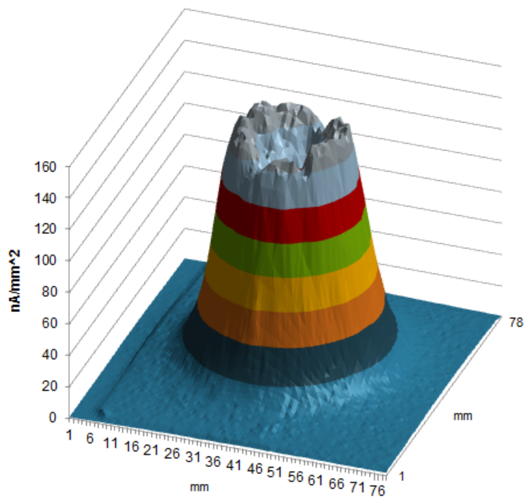



Figure 5b: Measured beam distribution on target with and without rastering, 117 MeV (Foil phosphor images with beam, 12/24/2015). Same as Figure 5a but with similar y-scales for both plots.

Beam distribution on target, 117 MeV, 155 µA
(Foil phosphor image with beam, 3/25/2016)




Beam distribution with raster
FWHM: 34 mm
FWTM: horiz: 57 mm, vert: 55 mm

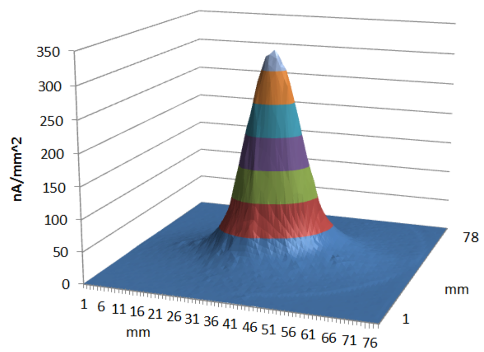
Repeating raster pattern:

- 4 linac beam pulses at 12.5 mm (155 amps peak)
- 1 linac beam pulse at 5.5 mm (71 amps peak)

This phosphor image was taken after non-rastered beam profile was decreased to:
FWHM: 10 mm
FWTM: 23 mm

Figure 6: Measured beam distribution on target with raster on, 117 MeV (Foil phosphor images with beam, 3/25/2015). Non-rastered beam profile was decreased so that outside radius could be increased by 1 mm from 11.5 mm to 12.5 mm. This provides an increase in the rastered beam FWHM, while decreasing the FWTM, resulting in less beam spilling outside the RbCl target diameter of 60 mm. Note that the center of this rastered profile shows a crater. If deemed necessary, the raster pattern can be modified to more evenly distribute the beam in this area.

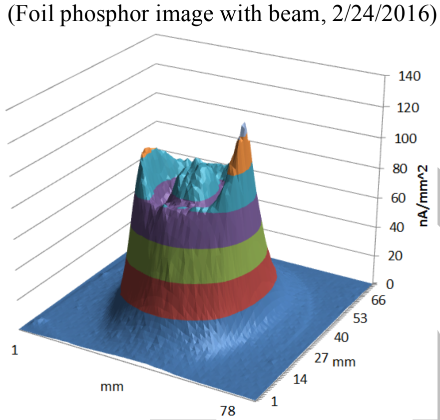
Beam distribution on target, 200 MeV, 115 µA
(Foil phosphor image with beam, 2/24/2016)




Beam distribution without raster
FWHM: 15 mm horizontal, 12 mm vertical
FWTM: 23 mm horizontal, 26 mm vertical

Figure 7: Measured beam distribution on target with raster off, 200 MeV (Foil phosphor image with beam, 2/24/2016)

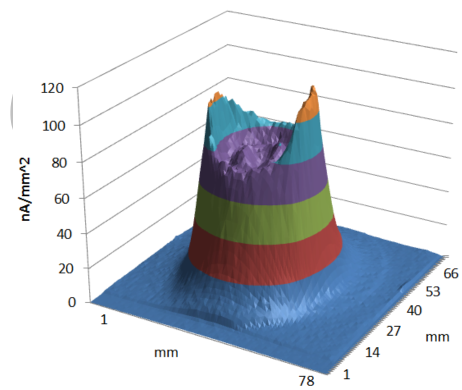
Beam distribution on target, 200 MeV, 140 µA
(Foil phosphor image with beam, 2/24/2016)




Beam distribution with raster
FWHM: 37 mm horizontal, 35 mm vertical
FWTM: 56 mm horizontal, 47 mm vertical

Repeating raster pattern:
- 4 linac beam pulses at 13.5 mm (225 amps peak)
- 1 linac beam pulse at 4.5 mm (75 amps peak)

Beam distribution on target, 200 MeV, 140 µA
(Foil phosphor image with beam, 2/25/2016)




Beam distribution with raster
FWHM: 34 mm horizontal, 35 mm vertical
FWTM: 59 mm horizontal, 50 mm vertical

Repeating raster pattern:
- 4 linac beam pulses at 13.5 mm (225 amps peak)
- 1 linac beam pulse at 5.5 mm (92 amps peak)

Figure 8: Measured beam distribution on target with raster on, 200 MeV, showing difference between 2 different radius patterns. Note that the image on the right with 5.5 mm inside radius has a crater in the center, while the image on the left with 4.5 mm inside radius does not. Optimal beam raster patterns continue to be explored. The pattern is programmed by entering a list of radii in a table. The radius is changed to the next table setting after each LINAC pulse (6.67 Hz) and the table pattern repeats. This provides the capability to program complicated raster patterns if desired. The peaks on the left and right of each image, which are at the top and bottom on the target, are caused by the horizontal sweeping of the beam due to energy differenced from the beginning to end of the beam pulse. Reference figure 11 below for additional details. This horizontal beam motion was minimized when the 117 MeV images in figures 5 and 6 were taken.

## 5.1. Beam Instrumentation Data

Several plots of data acquired with the new BLIP beam instrumentation devices are shown below, including the beam current transformer, beam position monitor (BPM), the laser profile monitor (LPM), and the multiwire profile monitors.

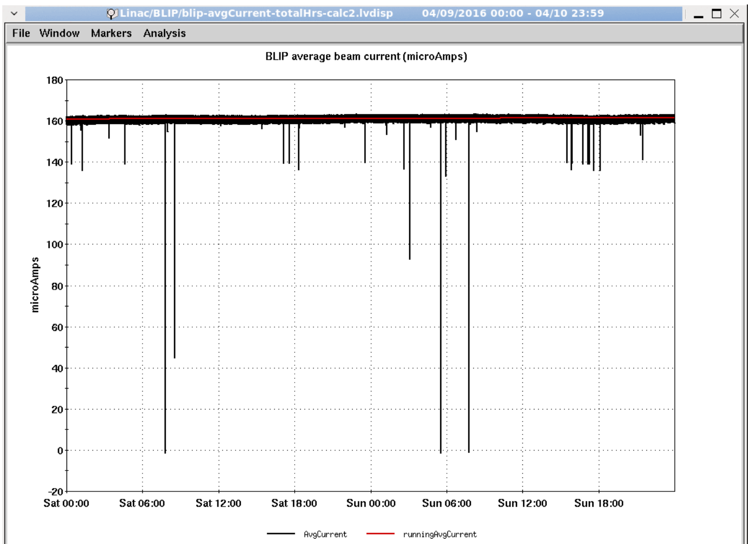



Figure 9: A 48-hour period (April 9-10, 2016) of the average beam current (black), and the running average (red) for 117 MeV Sr-82 production with the raster system on. Note that the average beam current is nearly steady at 160 μA for the entire period.

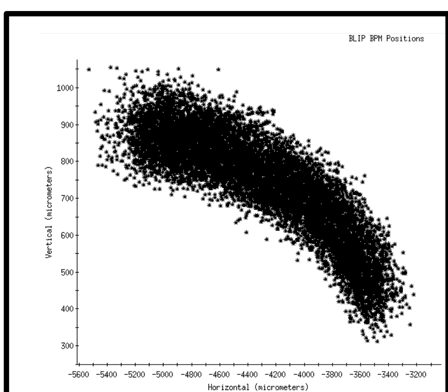



Figure 10: Horizontal vs. vertical beam position monitor data for several beam pulses with raster off at 117 MeV beam energy. The raw BPM data for each beam pulse is divided into about 110 slices, and the position of each slice is calculated and plotted. Note that the scales are different in each plane. The actual positions at the BPM are about 1.8 times that shown in the plots.

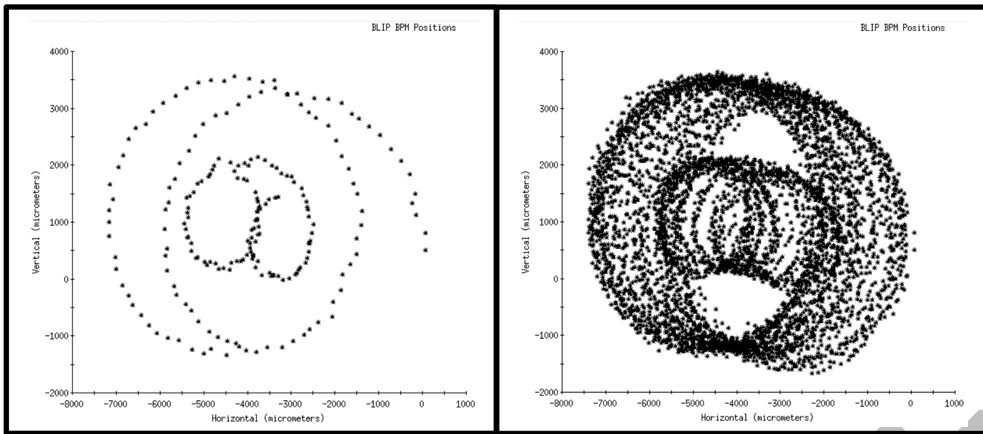



Figure 11: Beam position monitor data, horizontal vs. vertical. Left plot shows data for one beam pulse 11.5 mm at the target and one beam pulse at 4.5 mm at the target with 117 MeV beam. The right plot shows many pulses with the same beam conditions. The actual positions at the BPM are about 1.8 times that shown in the plots. The nearly-horizontal sweeping motion is due to beam loading that causes energy differences from the beginning of the beam pulse to the end of the beam pulse, resulting in different angular kicks at the bending magnet BM1. This motion is also noted in Figure 10 above with the raster off.

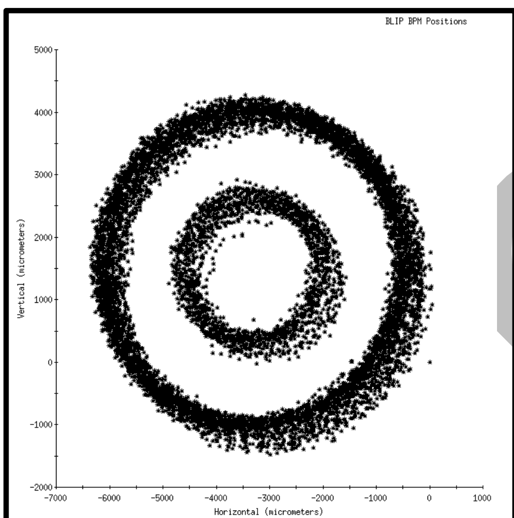



Figure 12: Beam position monitor data, horizontal vs. vertical, after adjusting the bending magnet BM1 power supply to time the power supply current pulse edge to compensate for the beam loading effect. Note that most of the horizontal sweeping motion is now gone. This plot was taken on March 30, 2016 with 117 MeV beam and raster pattern radii of 12.5 mm and 5.5 mm at the target. Again, the actual positions at the BPM are about 1.8 times that shown in the plots.

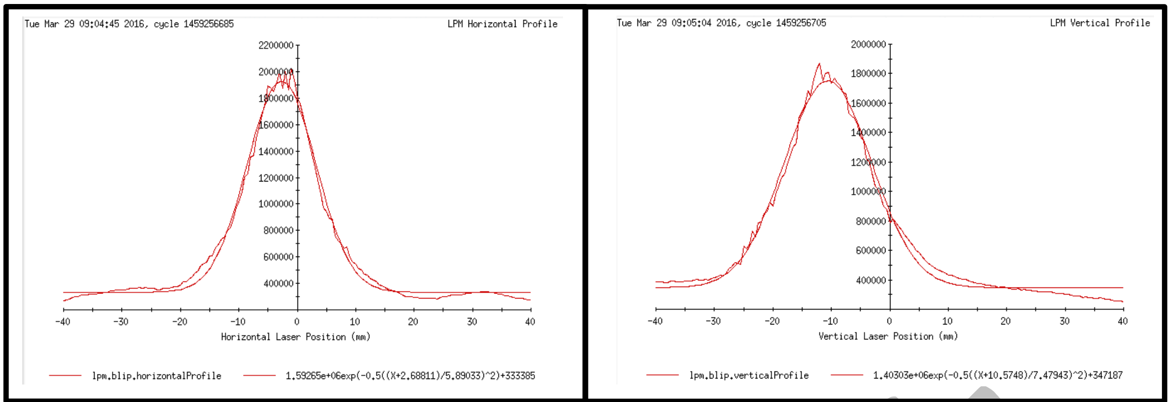



Figure 13: Horizontal (left) and vertical (right) BLIP laser profile monitor data with curve fits, with raster on. The y-scale is arbitrary units but is proportional to the number of electrons collected at each laser position. In these scans, the distance between each data point is 0.5 mm. A total number of 161 laser positions are provided. Each position value is the average of 24 points, where each point is a narrow slice of one beam pulse.

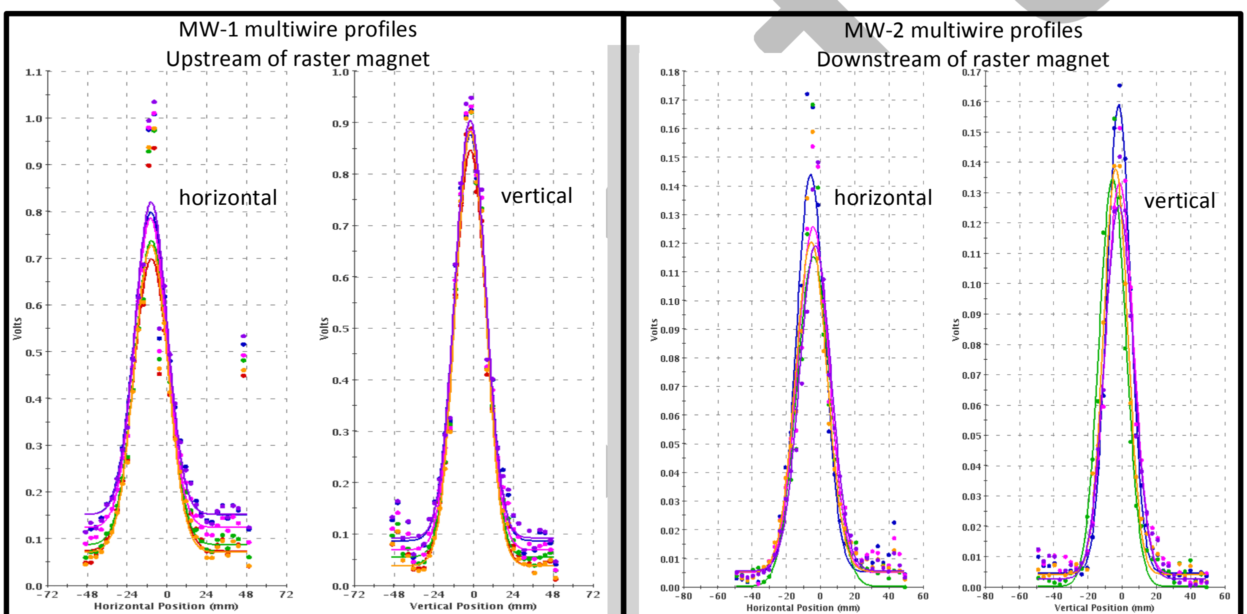



Figure 14: BLIP horizontal and vertical multi-wire profile measurements for MW-1 (left) and MW-2 (right). Profiles for six beam pulses are overlaid in each plot. The y-scale is the integrated signal strength for each wire. The wire spacing is 3.175 mm and each plane has 32 wires. These profiles were taken with 117 MeV and with the raster on. Note that all overlaid profiles for MW-1 (which is located upstream of the raster magnet) are well aligned, while the overlaid profiles for MW-2 (which is located downstream of the raster magnet) are shifted with respect to each other. This is the expected beam raster behavior.

# 6. Transition to operations / Recommended spending of remaining funds

As the project transitions to operations, $649.9k of project funding remains, including contingency.

We propose using this remaining funding as follows:

| Description | Estimated total cost (burdened) |
|---|---:|
| Highest priority spares as outlined in section 6.1 | $295,200 |
| BM1 bending magnet power supply replacement as detailed in section 6.2 | $249,000 |
| Analysis of Gallium target failures as detailed in section 6.3 and Attachment A | $100,000 |
| Reserve | $5,500 |
| | |
| TOTAL: | $649,700 |

Other lower priority spares detailed in section 6.4 totaling $294,500 are recommended to be purchased at some point in the future. The goal is to purchase these spares within the next several years to ensure that spares are on-hand as equipment ages and failures become more likely.

## 6.1. Highest priority recommended spares

The table below lists the highest priority recommended spares.

| Description | Qty | Probability of failure (low/medium/high) | Consequence of failure | Lead time | Estimated total cost (burdened) |
|---|---|---|---|---|---:|
| 1. Raster power supply spares | | | | | |
| 1.1 Power amplifier | 1 | Medium | No rastering | 12 weeks | $39,000 |
| 1.2 Matching transformers | 2 | Medium | No rastering | 12 weeks | $9,600 |
| 1.3 Resonating capacitors | 12 | Medium | No rastering | 16 weeks | $7,900 |
| 1.4 Voltage sensing xformers | 4 | Medium | No rastering | 8 weeks | $3,200 |
| 1.5 PXIe controls | 1set | Medium | No rastering | 6 weeks | $43,500 |
| 2. Raster magnet | | Medium | No rastering | 24 weeks | |
| 2.1 Ferrites | 4 | | | 8 weeks | $24,800 |
| 2.2 Machined parts | 1set | | | 8 weeks | $26,400 |
| 2.3 Labor (eng, design, assy) | | | | 8 weeks | $118,300 |
| | | | | | |
| 3. Instrumentation | | | | | |
| 3.1 ACCT PXIe controls | 1set | Medium | Loss of beam current measurement, totals and interlock | 6 weeks | $16,000 |
| 3.2 LPM laser fiber optic cable | 1 | High | Loss of LPM beam profile measurements | 6 weeks | $6,500 |
| | | | | TOTAL: | $295,200 |

### 6.2. BM1 bending magnet power supply replacement

Another very high priority item that is recommended to be purchased with the remaining project funding is a new bending magnet power supply for BM1, which is the magnet used to bend the beam horizontally into the BLIP beamline.

The total estimated burdened cost for this is $249,000, including the power supply itself, related control hardware, software development, installation and labor. The presently installed power supply is quite old and problematic. The output current drifts continuously and requires ongoing manual adjustments to ensure that the beam pulse stays on the target. A replacement power supply will provide increased stability in terms of beam position on the target, resulting in increased total integrated current on the target.

### 6.3. Investigation plan for Gallium target failure analysis

The plan for analyzing the Gallium target failures is provided in Attachment A. The cost estimate is summarized in the table below.

| **Description** | **Estimated total cost (burdened)** |
|---|---|
| New Ga targets | $2,000 |
| Replicant studies | $4,000 |
| Target for irradiation studies | $3,000 |
| Tantalum targets | $21,000 |
| Irradiation time | $20,000 |
| Personnel time | $50,000 |
| | |
| TOTAL: | $100,000 |

### 6.4. Other recommended spares

Other lower priority recommended spares for future purchase are listed in the table below.

| Description | Qty | Probability of failure (low/medium/high) | Consequence of failure | Lead time | Estimated total cost (burdened) |
|---|---|---|---|---|---|
| 2. Raster magnet | | | | | |
| 2.4 Beam tubes | 2 | Medium | | 8 months | $43,600 |
| 2.5 Beam tube coating | 2 | | | 3 months | $23,400 |
| | | | | | |
| 3. Instrumentation | | | | | |
| 3.3 Multiwire units | 2 | Medium (high after 5 years of operation) | No beam trajectory angle and position | 7 months | $97,000 |
| 3.4 Beam current transformer | 1 | Low (high after 10 years of operation) | No beam current measurement | 6 months | $42,000 |
| 3.4 LPM laser | 1 | medium | Loss of LPM beam profile measurements | 12 weeks | $37,000 |
| 3.5 LPM current preamplifier | 1 | medium | Loss of LPM measurements | 6 weeks | $3,500 |
| 3.6 Beam Position Monitor vacuum chamber | 1 | low | Loss of position measurements | 20 weeks | $48,000 |
| | | | | | |
| | | | | TOTAL: | $294,500 |

## 7. ESSH&Q (Environmental, Safety, Security, Health and Quality)

As a result of the NEPA review performed prior to beginning the BLIP Raster project, evidence showed that as the LINAC average beam currents increase, soil contamination areas could be larger and contamination of rainwater infiltrating the contaminated soil and entering the groundwater has a higher likelihood of occurring. In order to mitigate this potential contamination, the soil cap over areas of the beam-line has been extended using BLIP Raster project funding.

Both the Radiation Safety Committee (RSC) and the Accelerator Systems Safety Committee (ASSRC) conducted reviews of the project to ensure that all aspects of safety were identified, addressed and approved. These reviews considered conventional safety issues, electrical compliance and shielding approval, and included walkthroughs of the BLIP control room and the fully assembled beam-line prior to operating the system.

The BLIP beam-line tunnel area is one of the highest radiation areas at Brookhaven National Lab. Therefore, installation of the new BLIP Raster system required considerable work planning to ensure the safety of all workers and keep the total dose rates as low as reasonably achievable. The estimated total dose for the project installation work was 2000 person mrem. The actual accumulated dose was 2068 person mrem. Approximately 50 people worked under the project RWPs (radiation work permits), with a resulting average of less than 50 mrem per person.

The beam-line and associated equipment were preassembled in a non-radiation lab environment to decrease time required for installation in the high radiation beam tunnel. This proved to be very beneficial because it enabled engineers and technicians to slowly and carefully resolve assembly issues without the concern of dose accumulation.

Prior to beginning the installation in the tunnel, Radiation Control Division (RCD) staff successfully decontaminated the primary work area. This prevented the need for workers to wear contamination PPE (Personal Protective Equipment), thus making work in the area more efficient and limiting accumulated dose.

RCD staff also installed temporary shielding to limit dose rates in the tunnel work area.

The entire team worked diligently and safely, with zero occurrences of injury during the project lifecycle.

## Attachment A - Investigation plan for Gallium target failures

**Introduction**

The BNL Isotope Program has experienced high failure rates with niobium encapsulated Ga metal targets used to produce Ge-68. There is no clear mechanism of failure. In the past BLIP beam intensities over 90µA were problematic. Only by keeping beam intensity at 80µA or less did the targets survive, leading to low production rates for both Ge-68 and Sr-82. There was a recent failure (January 2016) of a Ga target irradiated with the new raster even though power density was much lower than in the past. Factors that are being considered that may be responsible include: attack of the Nb by liquid gallium, high pulse power of the beam, temperature, and cavitation. Cavitation is a problem noted with liquid targets and may be the reason for the Ga target failures**. (**Cavitation of SNS targets has been observed to cause pitting of stainless steel window at its interface with mercury). However power density at BLIP is many orders of magnitude less than at SNS. The investigation plan includes:

1) **Fabrication of new targets:** The targets previously used were over 3-4 years old. The age of the target may have led to window corrosion. This is further backed up by examination of the windows in which the Ga metal could not be removed and appeared amalgamated to the window. Fresh targets will be fabricated and tested in beam**. (Cost: $2000/2 targets)**
2) **Follow up on ORNL Experience**
   - Discussions were held with Bernie Reimer at ORNL to discuss how they observed and attempted to correct for cavitation.
   - Address the numbers of grains across the thickness of Nb window (0.012" thickness maybe too thin - evaluate at CFN through electron microscopy). **(Nick Simos and postdoc time)**
   - Use surface replicant to evaluate window surfaces of the gallium target for evidence of cavitation. Replicant is a liquid that will be applied to the surface of the failed target window that has been cleaned to get rid of removable contamination solidified replicant is then sent out for evaluation at ORNL. **(Cost:$400.00)**
3) **Scanning Electron Microscopy Activity:** Engaging Dr. Nick Simos, BNL a materials expert with familiarity of this program, to perform testing of the niobium metal at different temperatures; with and without contact to Ga to evaluate Nb window. A series of experiments have been initiated at the Center of Functional Nanomaterials to study the evolution of the microstructure of Niobium with temperature with and without contact with Gallium. The grain-size of the Nb used to fabricate the windows of the Gallium capsules will be evaluated (TEM-size samples will be made and studied under Transmission Electron Microscope at CFN to compliment the SEM studies) to enable correlation with experimental data on cavitation of stainless steel windows in contact with mercury at SNS. **(Nick Simos and postdoc time).**

4) **Proton Irradiation Damage to Niobium Microstructure:**

To delineate the contributing factors the effect of proton irradiation on the Niobium microstructure, which may potentially lead to Niobium being more vulnerable to Gallium attack, a replication of the irradiation conditions will be made. Specifically a specially designed capsule to replace the beam stop downstream of the RbCl targets has been designed and fabricated. The capsule contains three layers of materials under vacuum that are selected to fully degrade and stop the proton beam leaving the second RbCl target. The first layer consists of specially designed Nb strips made out of the same stock of material used in the Gallium-containing targets and of the same thickness as the capsule window (0.012"). The two layers downstream of the Nb layer consist of graphite and steel selected to (a) keep Nb in place and in contact with the front window (where the proton energy is very similar to the energy the Nb-Gallium interface sees) and (b) fully degrade and stop the remaining beam within the capsule. **(Cost target encapsulation: $2-3000.00, Chris Cullen's time to run thermal analysis)**

5) The experimental effort will be accompanied by a numerical simulation study emulating the exact conditions during irradiation and using a thermo-mechanical analysis of the gallium-Nb capsule. The effort relies on the capabilities of the LS-DYNA computational code that enables fluid-structure interaction via an Arbitrary Lagrangian-Eulerian (ALE) formulation with proton beam energy deposition on the materials deduced from neutronic codes (FLUKA) and integrated into the LS-DYNA simulation of the irradiation conditions and geometry.**(Cost Nick Simos and postdoc time)**

6) To assess impact of corrosion we are looking at tantalum as an alternative window material as it is resistant to attack by Ga to higher temperatures than Nb. In addition the existing targets were fabricated some time ago. We have some that have not been put into beam and are 3-4 years old. We will open those targets and evaluate for corrosion. A freshly prepared Nb/Ga target will also be tried in beam. (**Cost technician time to evaluate Ga target, Production of Tanatalum targets $21,000.00, Chris Cullen's time to perform thermal analysis on Tantalum target)**

7) Looking into Ga alloys that could be used for irradiation such as GaNi (solubility problem). **(Cost: Evaluations will need to be performed by postdoc, target arrays will need to be prepared by Dr. Dmitri Medvedev and thermal analysis will need to be done by Chris Cullen.**